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A PILOTED FIXED-BASE SIMULATOR STUDY OF LOW-SPEED FLIGHT CHARACTERISTICS OF AN ARROW-WING SUPERSONIC TRANSPORT DESIGN

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SUMMARY

A piloted fixed-base simulator study has been made to determine the low-speed flight characteristics of an arrow-wing supersonic transport configuration. The transport-type cockpit was equipped with normal flight controls and a flight instrument display representative of those found in current transport aircraft. The primary task used during the evaluation was the instrument approach. The flare and touchdown characteristics were not evaluated.

The results indicated that although the longitudinal short-period damping ratio was at a good level (0.84), the pitch damping appeared to be low to the pilot because of the low frequency of the short-period oscillation. This low pitch damping and the sluggish pitch response made the longitudinal handling qualities of the basic configuration unsatisfactory (Cooper rating of 6.5). When the static stability, the damping in pitch, the elevator effectiveness, and the elevator to column gearing were increased by a sufficient amount, the Cooper rating was improved to 2.5.

The lateral-directional handling qualities of the basic configuration were said to be unacceptable (Cooper rating of 8.5) because of the poor roll control characteristics and the uncontrollable Dutch roll. When the effective dihedral was decreased by a sufficient amount, and the damping in roll and yawing moment due to roll were increased by a sufficient amount, the Cooper rating was improved to 2.5.

INTRODUCTION

The feature point of the supersonic transport (SST) is its tremendous speed advantage over the present subsonic jet transports. Unfortunately, configurations designed for high-speed flight do not usually possess good low-speed handling characteristics. In fact, low-speed control and high-speed performance normally detract from each other. Therefore, careful attention must be given to the design of the SST in order to build an airplane that is feasible for operation in the high-speed range and that can still be flown safely during take-offs and landings.

One SST design that has been proposed has a highly swept ($\Lambda = 74^\circ$) arrow planform wing, and the present study was undertaken to determine the low-speed flight characteristics of this design. It should be mentioned, however, that although this arrow-wing SST was a particular design, the general size, weight, and moments of inertia are representative of a range of SST designs. The low-speed flight characteristics of the subject SST concept were studied in the power approach condition by utilizing a fixed-base simulator. The primary task used during the evaluation was the instrument approach. Measured low-speed wind-tunnel aerodynamic data, as well as variations therefrom, were used as inputs. Two pilots "flew" the simulator to evaluate the stability and control characteristics of the basic configuration as well as to determine the values of the aerodynamic parameters that would be required to make the handling qualities satisfactory (Cooper rating of $3\frac{1}{2}$ or less).

The low-speed handling qualities of the SST configurations studied are compared with those of various SST configurations studied during an in-flight simulation program (ref. 1), with those of current subsonic jet transports, and with existing handling qualities criteria. It has been generally agreed that no degradation of handling qualities from those of current jet transports would be acceptable for normal operation of supersonic transports. Throughout the present study no attempt was made to optimize the handling qualities of any particular axis; an attempt was made only to determine values of the aerodynamic parameters required for satisfactory handling qualities.

SYMBOLS

In order to facilitate international usage of data presented, dimensional quantities are presented in both U.S. Customary Units and in the International System of Units (SI). The longitudinal aerodynamic characteristics are referred to the stability axes and the lateral-directional aerodynamics are referred to the body axes.

b	wing span, ft (m)
$C_{1/2}$	cycles required for oscillation to damp to one-half amplitude
C_D	drag coefficient
$C_{D,\alpha=0}$	drag coefficient at zero angle of attack
C_L	lift coefficient
$C_{L,\alpha=0}$	lift coefficient at zero angle of attack

C_l	rolling-moment coefficient
C_m	pitching-moment coefficient
$C_{m,\alpha=0}$	pitching-moment coefficient at zero angle of attack
C_n	yawing-moment coefficient
C_Y	side-force coefficient
$\bar{c}$	mean aerodynamic chord, ft (m)
F_c	force input to control column, lbf (N)
f_n	longitudinal short-period undamped natural frequency, cycles/sec (Hz)
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z axes, respectively, slug-ft^2 (kg-m^2)
I_{XZ}	product of inertia, slug-ft^2 (kg-m^2)
L_α	lift per unit angle of attack per unit of momentum, $C_{L_\alpha}\bar{q}S/mV$, per second
m	mass, slugs
n	normal acceleration, g units
P	period, sec
p	roll rate, radians/sec
q	pitch rate, radians/sec
$\bar{q}$	dynamic pressure, $\frac{1}{2}\rho V^2$, pounds/foot^2 (newtons/meter^2)
r	yaw rate, radians/sec
S	wing area, ft^2 (m^2)
s	Laplace operator

T	thrust, pounds (newtons)
$T_{1/2}$	time to one-half amplitude, sec
T_2	time to double amplitude, sec
T_R	roll time constant, sec
V	airspeed, knots or ft/sec
v_e	equivalent side velocity, ft/sec (m/sec)
W	weight, lbf (N)
α	angle of attack, deg or rad
β	angle of sideslip, deg or rad
δ_a	aileron deflection, deg or rad
δ_c	column deflection, deg
δ_e	elevator deflection, deg or rad
δ_p	pedal deflection, in. (cm)
δ_r	rudder deflection, deg or rad
δ_w	wheel deflection, deg
ϵ_{gs}	glide slope error, deg
ϵ_{loc}	localizer error, deg
ζ_d	Dutch roll damping ratio
ζ_p	longitudinal long-period (phugoid) damping ratio
ζ_{sp}	longitudinal short-period damping ratio
θ	angle of pitch, deg

Λ angle of sweepback, deg

τ_E engine thrust time constant, sec

ϕ angle of roll, deg

ω_d undamped natural frequency of Dutch roll mode, radians/sec

ω_n longitudinal short-period undamped natural frequency, radians/sec

ω_ϕ undamped natural frequency appearing in numerator quadratic of ϕ/δ_a transfer function, radians/sec

$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$ $C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$ $C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$

$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}$ $C_{n_{\delta_a}} = \frac{\partial C_n}{\partial \delta_a}$ $C_{Y_{\delta_a}} = \frac{\partial C_Y}{\partial \delta_a}$

$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r}$ $C_{n_{\delta_r}} = \frac{\partial C_n}{\partial \delta_r}$ $C_{Y_{\delta_r}} = \frac{\partial C_Y}{\partial \delta_r}$

$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$ $C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$ $C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}}$

$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$ $C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$ $C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$

$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$ $C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}}$ $C_{m_{\Delta T}} = \frac{\partial C_m}{\partial \Delta T}$

$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha}$ $C_{D_\alpha} = \frac{\partial C_D}{\partial \alpha}$

$C_{L_{\delta_e}} = \frac{\partial C_L}{\partial \delta_e}$ $C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e}$

A dot over a symbol indicates a derivative with respect to time.

SIMULATOR

The simulator presented the pilot with essential elements of the task of performing an instrument landing system (ILS) approach. The transport-type cockpit was equipped with conventional flight and engine thrust controls and a flight instrument display representative of those found in current transport aircraft. (See fig. 1.) The simulator did not incorporate cockpit motion. There was no external visual display available; therefore, all approaches were terminated at an altitude of 200 feet (61 m) (flare and touchdown characteristics were not evaluated). Control forces were provided by a hydraulic servo system and were functions of control displacement and rate. The maximum travel of the controls, control breakout forces, and control force gradients are defined in table I. The gearings from cockpit control to control surface were: $\delta_e/\delta_c = -1.0$ to -6.0; $\delta_a/\delta_w = 0.75$; $\delta_r/\delta_p = -10^\circ/\text{in.}$ or $4^\circ/\text{cm}$. The thrust-throttle relationship and the engine response characteristics were represented by the equation $\frac{\Delta \text{ thrust}}{\Delta \text{ throttle}} = \frac{170{,}000 \text{ lbf}}{1 + s\tau_E}$, where τ_E was 0.2 second. In addition, a rate limit of 13,500 lbf/sec (60.05 kN/sec) was used on the thrust rate. (The $\frac{\Delta \text{ thrust}}{\Delta \text{ throttle}}$ gearing was 5000 lbf/deg or 22.24 kN/deg.) A general purpose analog computer was used with the simulator and was programed with the equations of motion for six degrees of freedom.

TEST CONFIGURATION

The airplane configuration used in this study had an arrow planform wing swept back 74°, twin outboard vertical tails, four engine nacelles located under the wing, leading-edge flaps (which were deflected downward 45°), a wing-apex notch, and a high-lift canard. A three-view sketch of the aircraft is presented in figure 2, and a detailed description of the configuration is given in reference 2. The effects of the canard on the low-speed flight characteristics were included in the study. The mass and dimensional characteristics of this SST design are presented in table II; the aerodynamic characteristics, taken from reference 2, are presented in table III. Note that the canard-off data are also presented. The canard-off configuration was evaluated only briefly, and the discussion herein applies to the canard-on configuration unless specifically stated otherwise.

EVALUATION PROCEDURES

All configurations were evaluated in two phases – general flying qualities and instrument landing system (ILS) approach task.

General Flying Qualities

Standard flight test procedures and techniques (ref. 3) were used in the evaluation of the longitudinal and lateral-directional flying qualities of each test configuration, and a Cooper rating was assigned for each axis. See table IV for the Cooper pilot rating schedule. It should be noted that throughout the study, pilot ratings are given separately for the longitudinal and the lateral-directional axes. The following is a list of the characteristics evaluated:

Longitudinal	Lateral-directional
1. Trimmability	1. Trimmability
2. Control force	2. Control forces
3. Control power	3. Control powers
4. Response and sensitivity	4. Response and sensitivity
5. Pitch damping	5. Roll damping
6. Short-period oscillations	6. Dutch roll oscillations
7. Long-period oscillations (phugoid)	7. Adverse yaw
	8. Spiral stability

Instrument Landing System Approach Task

The ILS approach was initiated with the aircraft in the power approach configuration (power for level flight) at an altitude of 2000 feet (0.6 km), an airspeed of 170 knots (210 knots for the canard-off configuration), and 10 statute miles (1.6 km) from the runway. The speeds were dictated by the maximum touchdown angle of attack ($\alpha = 12^{\circ}$). The cockpit indicator presented localizer and glide-slope deviation only; the initial conditions placed the aircraft offset to the left of the localizer and below the glide slope. (See fig. 3.) The glide slope used throughout the program was 2.7°. The pilot's task was to capture the localizer and glide slope and to maintain them as closely as possible until the 200-foot (61-m) altitude termination point was reached. No crosswinds or turbulence were introduced throughout the test program; however, 200-foot (61-m) offsets (both laterally and vertically) were introduced at random intervals during the approach. By correcting for these random offsets, the pilot was able to see how quickly and easily the aircraft could return to the desired position.

RESULTS AND DISCUSSION

The low-speed flight characteristics of the subject arrow-wing SST design are presented and discussed in relation to pilot ratings and opinions. Two pilots participated in the simulation program, the primary pilot flying all configurations and the secondary pilot flying only the more pertinent ones. For the configurations evaluated by both pilots, the Cooper pilot ratings assigned were within one-half of a rating and therefore, for simplicity throughout the discussion of the results, only the ratings assigned by the primary pilot will be presented.

Basic Canard-On Configuration

The pilot rating assigned to the longitudinal handling qualities of the basic configuration was 6.5, the major objections being sluggish initial pitch response and low pitch damping. A pilot rating of 8.5 was assigned to the lateral-directional handling qualities, the major objections being the poor roll response, low roll damping, and the uncontrollable Dutch roll.

Longitudinal characteristics.- The pilots felt that the static stick-fixed and stick-free longitudinal stabilities were low; at an airspeed of 170 knots (approach speed), $\delta_c/\Delta V \approx -0.065$ deg/knot and $F_c/\Delta V \approx -0.18$ lbf/knot (-0.80 N/knot).

This configuration was somewhat difficult to trim. The difficulty seemed to be associated with the low pitch damping and the lack of static stability, which left the pilot hunting for correct attitude and airspeed. The aircraft was flown on the stable side (front side) of the thrust-required curve; the variation of thrust required with velocity $\left(\frac{\partial \frac{T}{W}}{\partial V}\right)$ was approximately +0.0002 per knot.

The dynamic stability characteristics of this configuration are presented in table V. As can be seen, the short-period damping ratio was $\zeta_{sp} \approx 0.84$ which would normally be considered an indication of good pitch damping. (A short-period damping ratio on the order of 0.7 is said to be a good level.) However, as stated previously, the pilots commented that the damping in pitch was low for this configuration. This comment can be explained by noting, from table V, the low magnitude of the damping-in-pitch parameter $2\zeta_{sp}\omega_n$ which is approximately equal to 0.79. The value of $2\zeta_{sp}\omega_n$ is low because of the very low undamped natural frequency ω_n of the short-period motion, which was brought about by the combination of high pitch inertia $\left(I_Y = 26.5 \times 10^6 \text{ slug-ft}^2 \left(35.93 \times 10^6 \text{ kg-m}^2\right)\right)$ and the low level of static stability $\left(C_{m_\alpha} = -0.0372\right)$. Therefore, the pitch damping appeared to be low to the pilots because of the extremely long period (P = 24.8 sec) of the short-period motion. The short-period undamped natural frequency ω_n and damping ratio ζ_{sp} of this configuration are indicated in figure 4 and are compared with values representative of some subsonic jet transports. (The short-period characteristics indicated for the subsonic jet transports are normally considered acceptable by pilots.) As can be seen, even though the damping ratio of this basic SST configuration is what would be considered to be a good level, the value of ω_n is only approximately 50 percent of the average value indicated for the subsonic transports. This low value of ω_n, which appears to the pilot as low damping, is one of the major reasons the longitudinal handling qualities were assigned a Cooper rating of 6.5.

The longitudinal maneuver characteristics were considered to be adequate for any normal situation encountered during the approaches. For a steady pull-up maneuver, δ_c/n is approximately 15 deg/g, and F_c/n is approximately 42 lbf/g (187 N/g).

The pilots commented that the initial pitch response to column inputs was sluggish. This sluggish response, which was caused by the high pitch inertia, is illustrated in figure 5 and compared with the faster response of a subsonic jet transport. (The pitch time constants for this SST configuration and the subsonic transport are approximately 1.4 and 0.5 seconds, respectively.) The pitch control sensitivity $\dot{\theta}/\delta_c$ and maximum control power $\ddot{\theta}_{max}$ were considered to be poor by the pilots.

Lateral-directional characteristics.- As stated previously, the pilots assigned a Cooper rating of 8.5 to the lateral-directional handling qualities of the basic configuration. The pilots stated that the Dutch roll was very easy to excite, and once excited, was uncontrollable. The lateral-directional dynamic stability characteristics are presented in table V, and a Dutch roll time history is presented in figure 6. As can be seen, the Dutch roll is essentially undamped; the damping ratio ζ_d is approximately equal to 0.02 and the number of cycles required to damp to one-half amplitude $C_{1/2}$ is greater than 5. It can also be seen from figure 6 that the Dutch roll motion is predominantly rolling, that is, $\left|\frac{\phi}{\beta}\right| \approx 3.5$. $\left(\text{This compares with } \left|\frac{\phi}{\beta}\right| \text{ values from 0.5 to 1.5 for large subsonic jet transports.}\right)$ As stated in reference 4, a preliminary estimate of the magnitude of the parameter $\left|\frac{\phi}{\beta}\right|$ necessary for a good pilot rating has been developed from previous studies, including SST simulation programs; these tests indicated that the $\left|\frac{\phi}{\beta}\right|$ parameter should be less than 1.5 in order to obtain satisfactory pilot ratings.

The pilots commented that the damping in roll was low (poor). They could not make a change in bank angle and hold it at the desired position because of the poor roll damping; this inability to make precise bank angle changes also made the heading control poor. The roll control power and sensitivity were said to be adequate. The initial roll response was also said to be satisfactory; however the longer term roll response was unsatisfactory because the very high dihedral effect $\left(\text{large negative } C_{l_\beta}\right)$ amplified the Dutch roll which in turn adversely affected the roll rate after a short period of time. An illustration of the lateral response characteristics of this basic SST configuration is shown in figure 7, where the roll and yaw rate response to an aileron step input are presented as a function of time. The desired response to a step aileron (wheel) input, indicated by the dashed curves, should give an increase in roll rate to the maximum roll capability and at the same time the yaw rate should respond in the same direction without appreciable lag. For the basic configuration, however, undesirable oscillations in roll rate, as well as a lag in yaw rate response, were experienced as shown in figure 7.

Instrument landing system approaches.- Figure 8(a) shows a typical ILS approach for the basic SST configuration. As can be seen, the pilot was working constantly in an attempt to keep the aircraft trimmed and the wings level. The pilots commented that they could possibly land an aircraft having the longitudinal characteristics of the present configuration (PR = 6.5), although it would be quite difficult; however, they stated that they definitely could not safely land an aircraft with the lateral-directional characteristics of the present configuration (PR = 8.5).

Modified Canard-On Configuration

Some aerodynamic derivatives were varied in an attempt to make low-speed flight characteristics of this SST design satisfactory, and it was determined that several parameters had to be varied. In order to vary some of these parameters it would be necessary to modify the aircraft (for example, by increasing the size of the elevons) as well as to provide stability augmentation. To make the longitudinal handling qualities satisfactory the following changes were required: (a) an increase in the damping-in-pitch parameter C_{m_q} from -0.82 to -6.5, (b) an increase in the static stability parameter C_{m_α} from -0.0372 to -0.20, (c) an increase in the elevator control effectiveness parameter $C_{m_{\delta_e}}$ from -0.086 to -0.172, and (d) an increase in the elevator to column gearing δ_e/δ_c from -1.0 to -6.0. Although some of these changes appear to be quite large, the required $C_{m_{\delta_e}}$ could be achieved by increasing the size of the elevons chordwise and/or spanwise; once this requirement is satisfied, the apparent large change in C_{m_q} could be accomplished without saturating the effectiveness of the system. The pilot rating assigned to the longitudinal handling qualities of this modified SST configuration was 2.5, the only adverse comment being that the initial response was less than optimum.

To make the lateral-directional handling qualities satisfactory the following changes were required: (a) a decrease in the effective dihedral parameter C_{l_β} from -0.20 to -0.03, (b) an increase in the damping-in-roll parameter C_{l_p} from -0.11 to -0.50, and (c) an increase in the yawing-moment-due-to-roll parameter C_{n_p} from -0.055 to +0.040. The pilot rating assigned to the lateral-directional handling qualities of this modified SST configuration was 2.5.

Longitudinal characteristics.- The pilots stated that the static stick-fixed and stick-free longitudinal stability were adequate; at an approach airspeed of 170 knots, $\delta_c/\Delta V \approx -0.032$ deg/knot and $F_c/\Delta V \approx -0.088$ lbf/knot (-0.391 N/knot).

The dynamic stability characteristics of this modified SST configuration are presented in table V. The pilots stated that the pitch damping was good. (Note that the damping parameter $2\zeta_{sp}\omega_n$ is approximately 2.65 for this configuration as compared with 0.79 for the basic configuration.) It can also be seen from table V, as well as from figure 4 wherein the short-period characteristics of the various SST configurations evaluated are compared with some subsonic jet transports, that the damping ratio ζ_{sp} is greater than 1.0, which is probably higher than optimum since this deadbeat damping will affect the response of the aircraft. With regard to the response and damping of this configuration, one pilot commented: "There is a slight tendency to overshoot the desired pitch attitude when making large θ changes, but not when making small θ changes. This overshooting is caused by having to overcontrol in order to get the desired response."

The elevator to column gearing δ_e/δ_c was increased from -1.0 to -6.0, in order to improve the pitch response and sensitivity for this modified configuration. As stated previously, no attempt was made to optimize the handling qualities of any axis; however, an effort was made to optimize the δ_e/δ_c gearing for this particular modified configuration. Figure 9 presents a plot of pilot rating against δ_e/δ_c, and shows that as δ_e/δ_c is varied from -2.0 to -5.0, the pilot rating varied from 5.0 to 2.5, and that as the δ_e/δ_c was increased even farther from -6.0 to -8.0, the pilot rating begins to increase again $\left(PR = 2.5 \text{ for } \delta_e/\delta_c = -6.0 \text{ and } PR = 4.5 \text{ for } \delta_e/\delta_c = -8.0\right)$. These results indicate the maximum desired level and also show that for negative values larger than -6.0, the pilots felt that the control sensitivity became too high.

The longitudinal maneuver characteristics were considered to be adequate. For a steady pullup maneuver, δ_c/n is approximately 10 deg/g and F_c/n is approximately 27 lbf/g (120 N/g).

With $\delta_e/\delta_c = -6.0$ (optimum), the pitch response was said to be good for an aircraft of this size. The time constant for this modified configuration was 0.40 second, compared with 1.35 seconds for the basic configuration and 0.50 second for a large subsonic jet transport. (See fig. 5 for comparison of pitch response characteristics.)

Lateral-directional characteristics.- The pilots assigned a Cooper rating of 2.5 to the lateral-directional handling qualities of the modified configuration. The lateral-directional dynamic stability characteristics are presented in table V, and a time history of the Dutch roll is presented in figure 6. As can be seen, the damping ratio is at a good level $\left(\zeta_d \approx 0.2\right)$ and the roll-to-sideslip ratio $\left|\frac{\phi}{\beta}\right| \approx 0.17$. As mentioned earlier, previous studies have indicated that values of $\left|\frac{\phi}{\beta}\right|$ of less than 1.5 are considered satisfactory. The pilots stated that the Dutch roll was essentially nonexistent.

The roll response and damping were said to be good. (See fig. 7 for comparison of the lateral response characteristics of this modified configuration with those of the basic configuration.) The roll time constant was good; T_R is equal to 0.4 second as compared with 1.64 seconds for the basic configuration. The roll control power and sensitivity were also said to be good. The pilots commented that although there was no adverse yaw, there was adverse sideslip, but the adverse sideslip was said to be at an acceptable level. (For a roll control input to obtain 20° of bank to the left, approximately 4° of adverse sideslip was experienced.)

Instrument landing system approaches.- Figure 8(b) shows a typical ILS approach for the modified SST configuration. Upon comparing figure 8(b) with 8(a), which is a typical ILS approach for the basic configuration, it is obvious that the pilot "flew" the modified configuration much better and with much less effort.

Canard-Off Configuration

Longitudinal characteristics.- As mentioned previously, the canard-off configuration was tested only briefly. The pilot rating assigned to the longitudinal handling qualities of the basic canard-off configuration was 4.75, the major objection being the poor pitch damping.

The control power and sensitivity were said to be good and the pitch response was adequate. It should be noted that the elevator to column gearing was set at -6.0 since this was the optimum level established for the modified canard-on configuration. With the control gearing near optimum and with $C_{m_{\delta_e}}$ and C_{m_α} closer to the desired levels, the aircraft was much more responsive to column inputs than the basic canard-on configuration.

When the value of C_{m_q} was increased from -0.82 to -6.5, as was done for the canard-on configuration, a pilot rating of 2.5 was assigned to the longitudinal handling qualities.

Lateral-directional characteristics.- A pilot rating of 6.5 was assigned to the lateral-directional handling qualities of the basic canard-off configuration, compared with a pilot rating of 8.5 for the basic canard-on configuration. In general, the same comments regarding the lateral-directional handling qualities were given by the pilots for the basic canard-off configuration as were given and discussed for the basic canard-on configuration. The difference in the pilot ratings (6.5 as compared with 8.5) is attributed to the smaller dihedral effect for the canard-off configuration; the value of C_{l_β} is about 75 percent of that for the canard-on configuration, and as a result the Dutch roll and the lateral-control characteristics, in general, were not as unsatisfactory for the canard-off configuration. However, these characteristics were still said to be unacceptable and, because of these poor lateral-directional characteristics, the pilots were doubtful if this configuration could be landed safely.

When the values of C_{l_β}, C_{l_p}, and C_{n_p} were changed to -0.03, -0.50, and 0.04, respectively (the same as was done for the canard-on configuration), the pilots assigned a Cooper rating of 2.5 to the canard-off configuration.

Dynamic Stability Requirements and Criteria

For the past several years the aircraft industry has been aware that many of the existing stability requirements of aircraft have become outdated because of the expanding of flight envelopes and the increasing of airplane size. Although research is presently being conducted in an effort to remedy this situation, to date, essentially no clearly defined stability requirements and criteria have been established for aircraft similar to that for the supersonic transport. Therefore, in an effort to aid in the establishment of new stability requirements, the low-speed handling qualities of the SST configurations simulated in the present study are compared with those of various SST configurations studied during the in-flight simulation program of reference 1, with those of current subsonic jet transports, and with existing handling qualities criteria.

Longitudinal handling qualities criteria.- Numerous longitudinal handling qualities criteria have been proposed and used in the past, and some of these are presented in figure 10. The relationship of short-period frequency to short-period damping ratio has been considered in these four criteria, and none could be said to be adequate for the prediction of the flight characteristics of large aircraft. This situation is not surprising, however, since all of these criteria had different boundaries using the same stability parameters f_n and ζ_{sp}. This result would imply, therefore, that parameters other than frequency and damping ratio should be considered when attempting to establish longitudinal handling qualities criteria. Reference 7 pointed out one very significant additional factor, that is, the ability to change flight path with normal acceleration; this factor is related to L_α. By using this parameter and by recognizing that the pilot's mode of control is not constant for all flight regimes, a criterion for satisfactory short-period characteristics was developed that correlates well with current airplane experience, as well as with various simulation experiments. The criterion recommended in reference 7 is expressed as a plot of L_α/ω_n against ζ_{sp}. (It should be noted that the definition of L_α, as used in this case, is $L_\alpha = \frac{\bar{q}SC_{L_\alpha}}{mV}$, where C_{L_α} is measured per radian and V is in ft/sec or m/sec.) This criterion is presented in figure 11 where it is compared with the characteristics of the SST configuration evaluated in the present study, those evaluated during the in-flight simulation program of reference 1, and those of some subsonic jet transports. This criterion agrees with the results obtained during the present SST simulation program as well as with those from the other sources.

Lateral-directional handling qualities criteria.- Figure 12 presents the lateral-directional damping requirements defined in the Military Specifications, designated MIL-F-8785 (ref. 8), by using the reciprocal of the number of cycles required for the Dutch roll to damp to one-half amplitude $1/C_{1/2}$ and the ratio of roll to side velocity ϕ/v_e. The Dutch roll characteristics of the SST configurations evaluated during the present study, of the SST configurations presented in reference 1, and of some current large subsonic jet transports are related to the specifications in figure 12; as can be seen, the pilot evaluations for the various SST configurations of the present study are in agreement with the indicated boundaries.

Several recently published papers (ref. 9, for example) have evaluated the Dutch roll damping by using the parameter $\zeta_d \omega_d$ and relating it to pilot rating. The pilot-rating trends drawn on the basis of these studies are presented in figure 13. As can be seen, the basic SST configurations do not agree with these pilot-rating trends, whereas, the modified configurations agree reasonably well. The pilot ratings for the basic SST configurations do not agree with the boundaries dictated by reference 9, probably because a critical factor in the pilot ratings was the poor roll control characteristics. Consequently, the ratings in this case do not reflect an evaluation of the Dutch roll alone and could not be expected to agree with the Dutch roll criterion. The subsonic jet transports and the SST configurations presented in reference 1 agree with the results of reference 9 quite well.

Reference 10, which was a study of roll handling qualities, related pilot ratings to the roll time constant T_R. The shaded band in figure 14 represents fairings of test points from several investigations using both ground-based simulators and flight tests. Data for the SST configurations evaluated during the present study are also shown in figure 14 and it can be seen that, whereas the basic configurations did not agree with the results of reference 10, the modified configurations agreed very well. The noted disagreement is probably attributable to the poor Dutch roll and cross coupling characteristics, which are not considered in the results of reference 10.

Figure 15 presents the criterion for satisfactory cross coupling characteristics. Figure 15(a) relates the square of the roll coupling parameter $\left(\omega_\phi / \omega_d\right)^2$ to Dutch roll damping ratio ζ_d, as presented in reference 11, and figure 15(b) relates pilot rating to the roll coupling parameter ω_ϕ / ω_d, as presented in reference 12. The SST configurations evaluated during the present simulation study are indicated in these plots, and it can be seen that these SST characteristics agree with the results of both of the aforementioned references.

The spiral stability characteristics of the SST configurations simulated are indicated in figure 16, which presents the satisfactory, acceptable, and unacceptable boundaries presented in reference 13. As can be seen, all SST configurations studied fall within the "satisfactory" boundary. As discussed previously, the pilots found all of these SST configurations to possess satisfactory spiral stability characteristics; therefore, it can be said that the results of the present study agree with the criterion proposed in reference 13.

CONCLUDING REMARKS

Based on the results obtained during a fixed-base simulation program conducted to determine the low-speed flight characteristics of an arrow-wing supersonic transport, the following remarks are made summarizing the characteristics of the various configurations tested.

Canard-On Longitudinal Characteristics

The damping in pitch appeared to the pilots to be low. The short-period damping ratio was approximately 0.84 and would normally be considered an indication of good pitch damping, but the damping appeared to be low to the pilots because of the low frequency of the short-period oscillation which caused the damping-in-pitch parameter $2\zeta_{sp}\omega_n$ to be low. The initial pitch response was sluggish because of the high pitch inertia. This sluggish response and the low pitch damping made it difficult to make quick and precise glide-path corrections and resulted in an unsatisfactory rating for the longitudinal handling qualities of the basic SST configuration (Cooper rating of 6.5).

In order to make the longitudinal handling qualities of this configuration satisfactory, it was necessary to increase simultaneously the damping-in-pitch parameter C_{m_q}, the static stability parameter C_{m_α}, the elevator effectiveness parameter $C_{m_{\delta_e}}$, and the elevator to column gearing δ_e/δ_c. When these quantities were increased to suitable values, the Cooper rating was improved to 2.5.

Canard-On Lateral-Directional Characteristics

The Dutch roll was easily excited and essentially undamped. The roll characteristics were poor for two reasons; first, although the initial response was adequate, the large effective dihedral amplified the Dutch roll which in turn adversely affected the roll rate in a short period of time; and second, the damping in roll was low. Because of these unsatisfactory characteristics the lateral-directional handling qualities of the basic SST configuration were considered unacceptable (Cooper rating of 8.5).

By decreasing the effective dihedral parameter C_{l_β}, increasing the damping-in-roll parameter C_{l_p}, and changing the yawing-due-to-roll parameter C_{n_p} from a negative value to a positive value, the lateral-directional handling qualities of this canard-on configuration were made satisfactory (Cooper pilot rating of 2.5).

Canard-Off Flight Characteristics

The pilot rating assigned to the longitudinal handling qualities of the canard-off configuration was 4.75, the major objection being the poor pitch damping. A pilot rating of 6.5 was assigned to the lateral-directional handling qualities of the basic canard-off configuration. In general, the same comments regarding the lateral-directional flight characteristics were given by the pilots for this configuration as were given for the basic canard-on configuration.

Handling Qualities Criteria

The longitudinal handling qualities criteria involving only short-period frequency and damping ratio were found to be inadequate for the prediction of flight characteristics of large transport aircraft. One criterion, which involves short-period frequency and damping ratio and an effective flight-path response parameter, was in reasonable agreement with the results of the present study.

In general, the results of this study agreed with the various lateral-directional criteria presented, particularly the configurations rated satisfactory by the pilots.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 14, 1967,
720-01-00-08-23.

REFERENCES

1. Staff of Langley Research Center: Determination of Flight Characteristics of Supersonic Transports During the Landing Approach With a Large Jet Transport In-Flight Simulator. NASA TN D-3971, 1967.

2. Freeman, Delma C., Jr.: Low Subsonic Flight and Force Investigation of a Supersonic Transport Model With a Highly Swept Arrow Wing. NASA TN D-3887, 1967.

3. Anon.: Stability and Control. FTC-TIH-64-2004, U.S. Air Force, 1964. (Available from DDC as AD No. 443 699.)

4. Stapleford, Robert L.; Johnston, Donald E.; Teper, Gary L.; and Weir, David H.: Development of Satisfactory Lateral-Directional Handling Qualities in the Landing Approach. NASA CR-239, 1965.

5. Chalk, Charles R.: Additional Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter. WADC Tech. Rept. 57-719, Pt. II, ASTIA Doc. No. AD 206071, U.S. Air Force, July 1958.

6. Anon.: Aerospace Recommended Practice – Design Objectives for Flying Qualities of Civil Transport Aircraft. ARP 842, Soc. Automotive Engrs., Aug. 1964.

7. Shomber, H. A.; and Gertsen, W. M.: Longitudinal Handling Qualities Criteria: An Evaluation. AIAA Paper No. 65-780, Nov. 1965.

8. Anon.: Flying Qualities of Piloted Airplanes. Military Specification MIL-F-8785(ASG), Sept. 1, 1954; Amendment-4, Apr. 17, 1959.

9. Quigley, Hervey C.; Vomaske, Richard F.; and Innis, Robert C.: Lateral-Directional Augmentation Criteria for Jet Swept-Wing Transport Airplanes Operating at STOL Airspeeds. Conference on V/STOL and STOL Aircraft. NASA SP-116, 1966, pp. 295-310.

10. Ashkensas, I. L.: A Study of Conventional Airplane Handling Qualities Requirements – Part I. Roll Handling Qualities. AFFDL-TR-65-138, Pt. I, Nov. 1965.

11. Vomaske, Richard F.; Sadoff, Melvin; and Drinkwater, Fred J., III: The Effect of Lateral-Directional Control Coupling on Pilot Control of an Airplane as Determined in Flight and in a Fixed-Base Flight Simulator. NASA TN D-1141, 1961.

12. Ashkensas, I. L.: A Consolidation of Lateral-Directional Handling Qualities. AIAA Paper No. 65-314, July 1965.

13. Bisgood, P. L.: A Review of Recent Handling Qualities Research, and Its Application to the Handling Problems of Large Aircraft. Part I – Observations on Handling Problems and Their Study. Part II – Lateral-Directional Handling. Rept. No. Aero. 2688, Brit. R.A.E., June 1964.

TABLE I.- SIMULATOR CONTROL CHARACTERISTICS

Control	Maximum travel			Breakout force		Force deflection	
	deg	in.	cm	lbf	N	lbf/in.	N/cm
Column:							
Forward	9.9	5.50	13.97	3.5	15.6	5.0	8.8
Aft	20.5	9.94	25.25	3.5	15.6	5.0	8.8
Wheel	±130.0	±14.70	±37.34	2.0	8.9	3.0	5.3
Pedal		4.25	10.80	3.5	15.6	15.0	26.4

TABLE II.- MASS AND DIMENSIONAL CHARACTERISTICS

Weight, lbf (N)	300 000 (1 334 460)
Wing area, ft^2 (m^2)	6952 (646)
Wing span, ft (m)	109.2 (33.3)
Mean aerodynamic chord, ft (m)	84.8 (25.8)
Center-of-gravity location, percent $\bar{c}$	45.0
I_X, slug-ft^2 (kg-m^2)	2.85×10^6 (3.86×10^6)
I_Y, slug-ft^2 (kg-m^2)	26.50×10^6 (35.93×10^6)
I_Z, slug-ft^2 (kg-m^2)	29.60×10^6 (40.13×10^6)
I_{XZ}	0
Maximum control-surface deflections:	
δ_e (minus deflection required for trim), deg	±30
δ_a, deg	±15
δ_r, deg	±25

TABLE III. - AERODYNAMIC CHARACTERISTICS

Parameter	Canard-on basic	Canard-on modified	Canard-off basic	Canard-off modified
$C_{D,\alpha=0}$	0.0097		-0.0336	
C_{D_α}, per rad	.4111		.3644	
$C_{L,\alpha=0}$	.0045		-.1220	
C_{L_α}, per rad	2.0628		1.9482	
$C_{L_{\delta_e}}$, per rad	.2341		.1948	
$C_{m,\alpha=0}$	.0078	0.0419	.0384	
C_{m_α}, per rad	-.0372	-.2000	-.1834	
$C_{m_{\delta_e}}$, per rad	-.0860	-.1720	-.1261	
C_{m_q}, per rad	-.8200	-6.5000	-.8200	-6.5000
$C_{m_{\Delta T}}$, per lbf	0		0	
C_{l_β}, per rad	-.2006	-.0300	-.1501	-.0300
$C_{l_{\delta_\alpha}}$, per rad	-.0573		-.0521	
$C_{l_{\delta_r}}$, per rad	.0014		.0010	
C_{l_p}, per rad	-.1100	-.5000	-.1300	-.5000
C_{l_r}, per rad	.0800		.1900	
C_{n_β}, per rad	.0688		.0464	
$C_{n_{\delta_a}}$, per rad	-.0023		-.0029	
$C_{n_{\delta_r}}$, per rad	-.0378		-.0367	
C_{n_p}, per rad	-.0550	.0400	-.0650	.0400
C_{n_r}, per rad	-.1550		-.1850	
C_{Y_β}, per rad	-.2865		-.2292	
$C_{Y_{\delta_a}}$, per rad	-.0223		-.0201	
$C_{Y_{\delta_r}}$, per rad	.0602		.0550	
C_{Y_p}, per rad	.1550		.2650	
C_{Y_r}, per rad	.3250		.4000	

TABLE IV.- PILOT COOPER RATING SYSTEM

Mode of operation	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only: Failure of stability augmenter	Doubtful	Yes
Inoperable	Unacceptable	7	Unacceptable even for emergency condition: Failure of stability augmenter	No	Doubtful
		8	Unacceptable – Dangerous	No	No
		9	Unacceptable – Uncontrollable	No	No
Inoperable	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

TABLE V.- DYNAMIC STABILITY CHARACTERISTICS OF THE CANARD-ON SST CONFIGURATION

Basic		Modified	
Short period:	$\omega_n = 0.471$	Short period:	$\omega_n = 1.249$
	$P = 24.8$		
	$\zeta_{sp} = 0.843$		$\zeta_{sp} = 1.061$
	$2\zeta_{sp}\omega_n = 0.794$		$2\zeta_{sp}\omega_n = 2.650$
Long period:	$P = 62$	Long period:	$P = 69$
	$\zeta_p = 0.012$		$\zeta_p = 0.026$
Roll mode:	$T_R = 1.64$	Roll mode:	$T_R = 0.40$
	$T_{1/2} = 1.14$		$T_{1/2} = 0.28$
Spiral mode:	$T_{1/2} = 19.2$	Spiral mode:	$T_2 = 17.4$
Dutch roll:	$\omega_d = 1.16$	Dutch roll:	$\omega_d = 0.420$
	$P = 5.42$		$P = 15.36$
	$\zeta_d = 0.021$		$\zeta_d = 0.223$
	$C_{1/2} = 5.24$		$C_{1/2} = 0.483$
	$\left\lvert\frac{\phi}{\beta}\right\rvert = 3.59$		$\left\lvert\frac{\phi}{\beta}\right\rvert = 0.17$
	$\left\lvert\frac{\phi}{v_e}\right\rvert = 0.71$		$\left\lvert\frac{\phi}{v_e}\right\rvert = 0.03$
	$\left\lvert\frac{\omega_\phi}{\omega_d}\right\rvert = 0.374$		$\left\lvert\frac{\omega_\phi}{\omega_d}\right\rvert = 0.99$

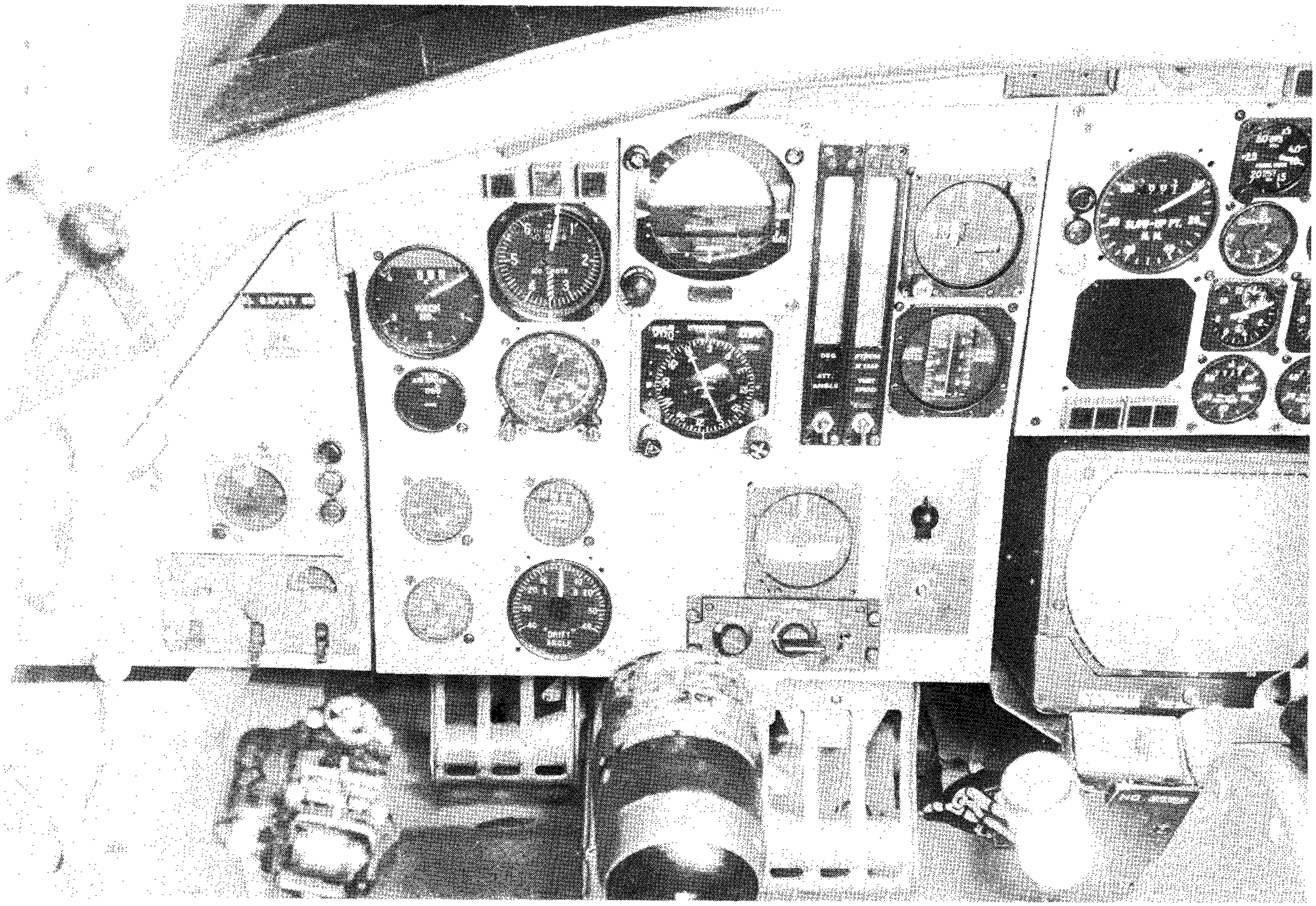


Figure 1.- Photograph of pilot's instrument display. L-66-6222

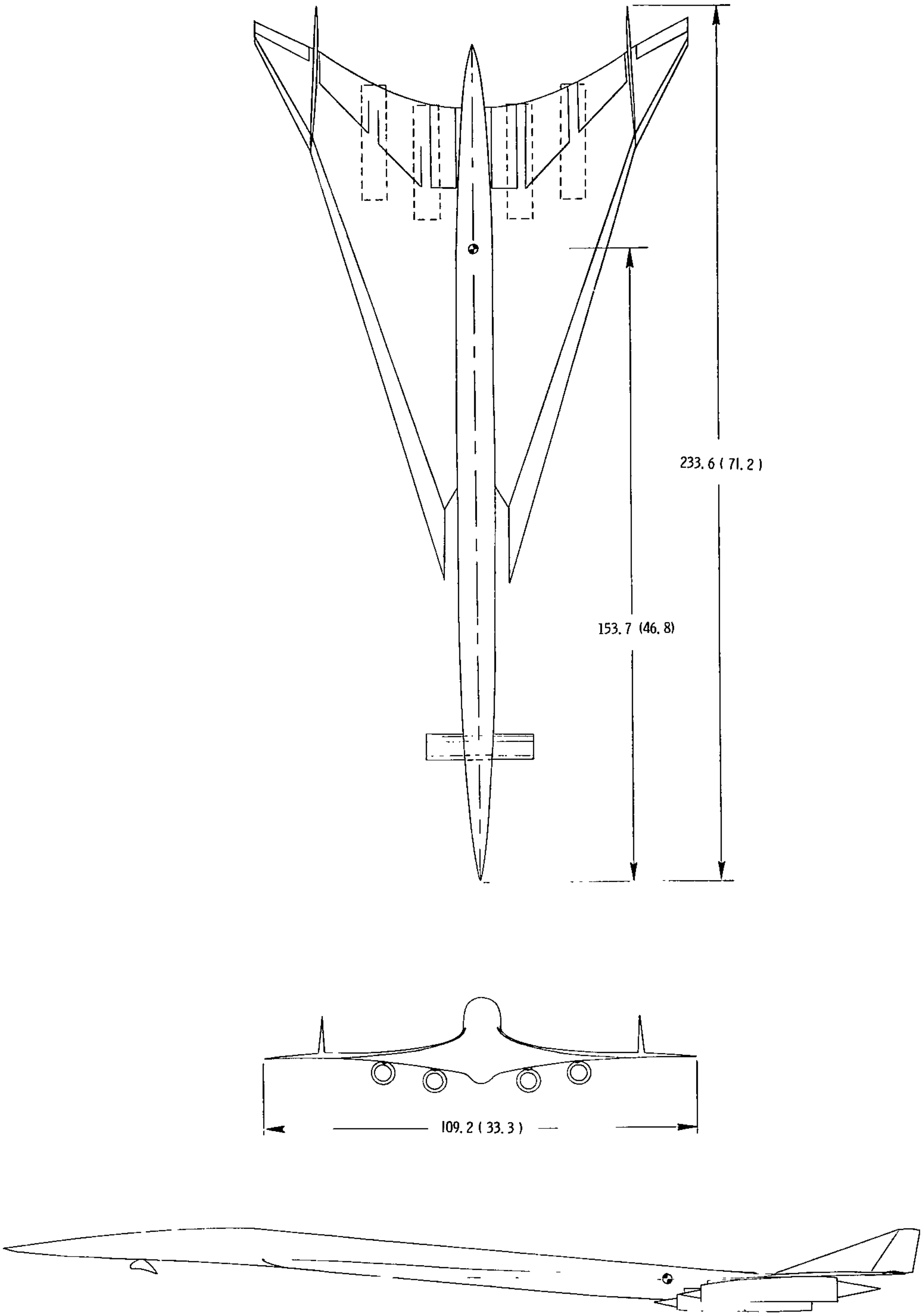


Figure 2.- Three-view sketch of SST design studied. (Dimensions are given in feet with meters indicated in parentheses.)

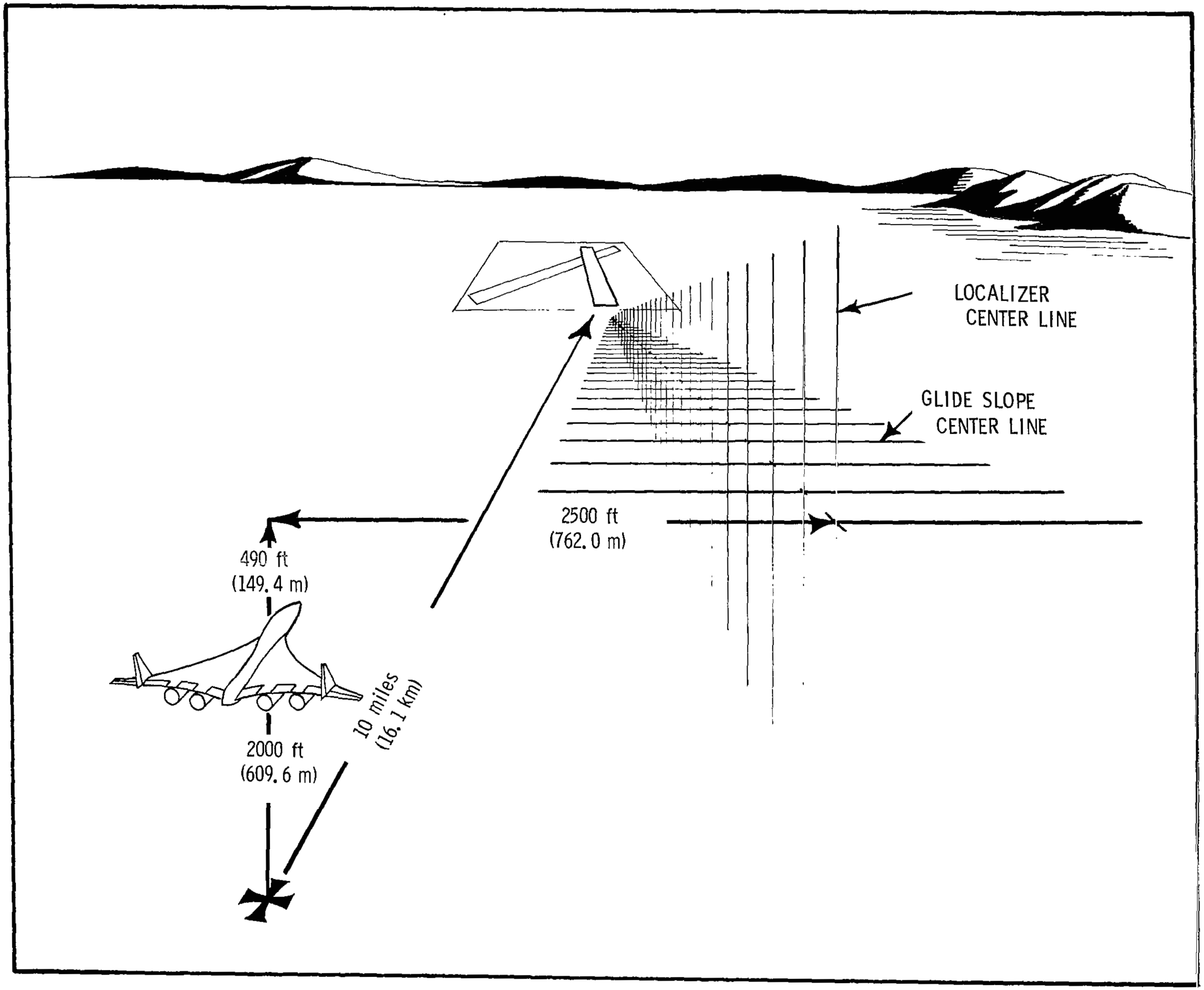


Figure 3.- Sketch indicating position of aircraft relative to runway, glide slope, and localizer at time zero.

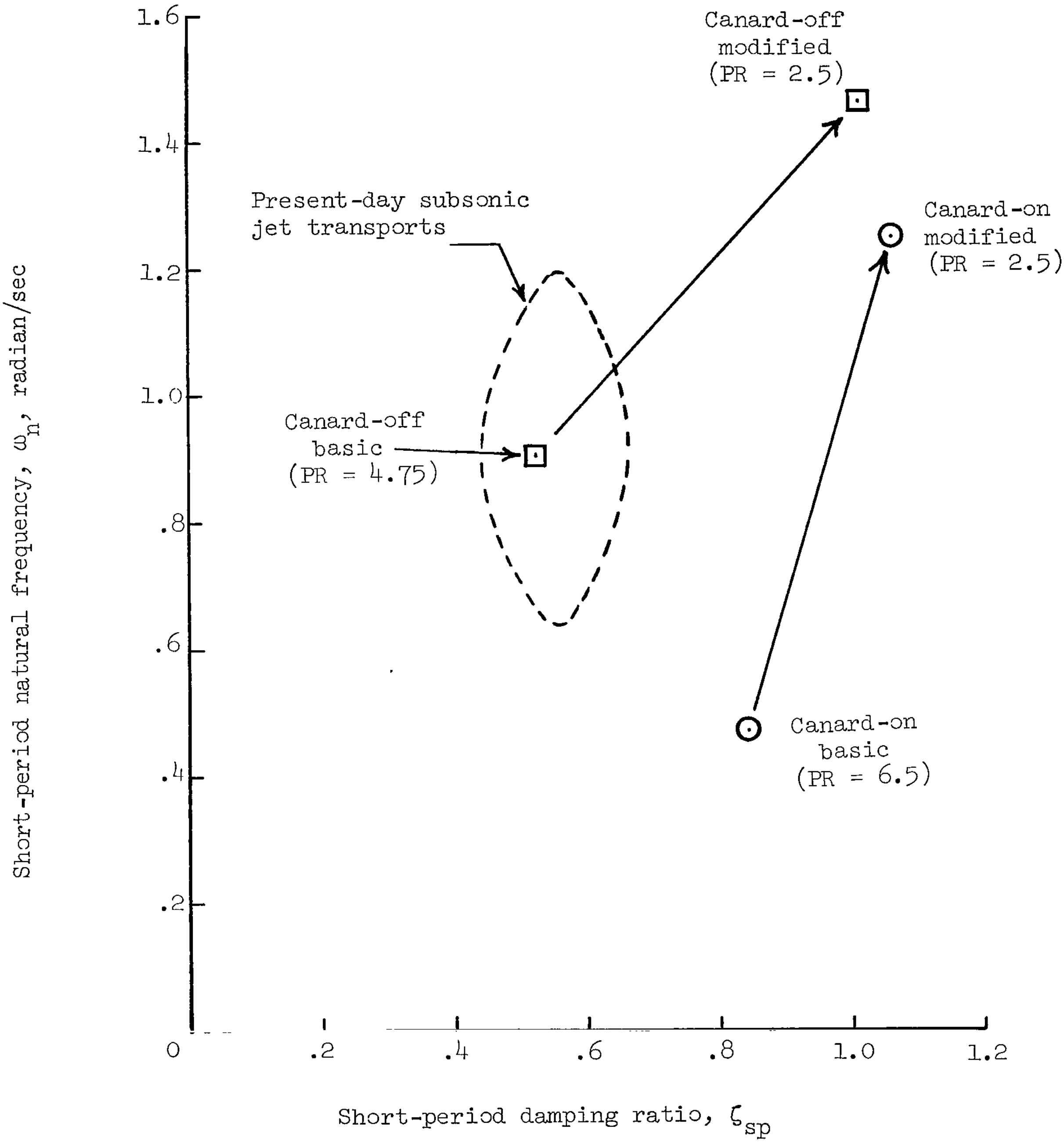


Figure 4.- Comparison of short-period frequency and damping ratio of the SST configurations simulated with that of present-day subsonic jet transports.

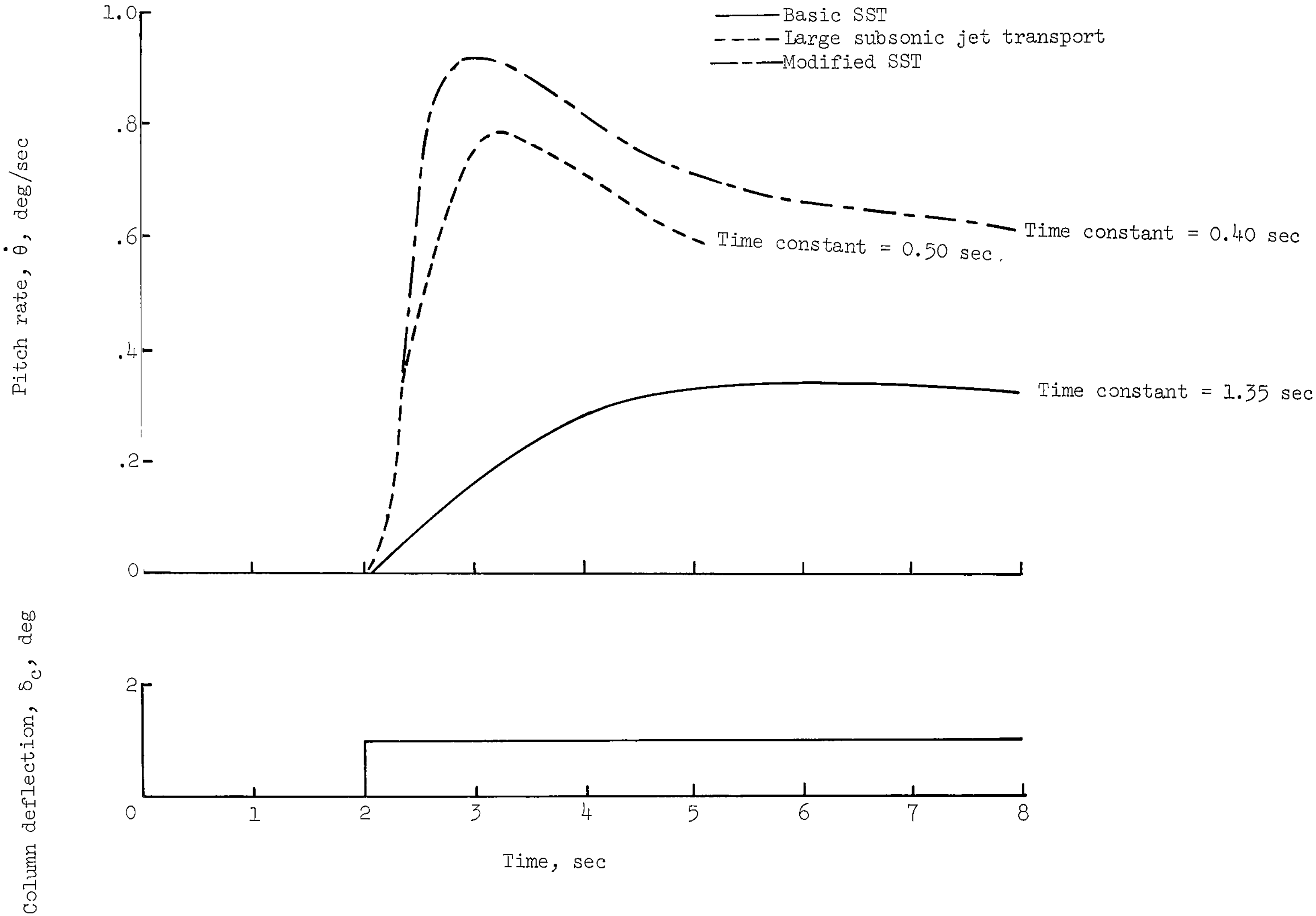


Figure 5.- Comparison of pitch response for the SST configuration with that of a large subsonic jet transport.

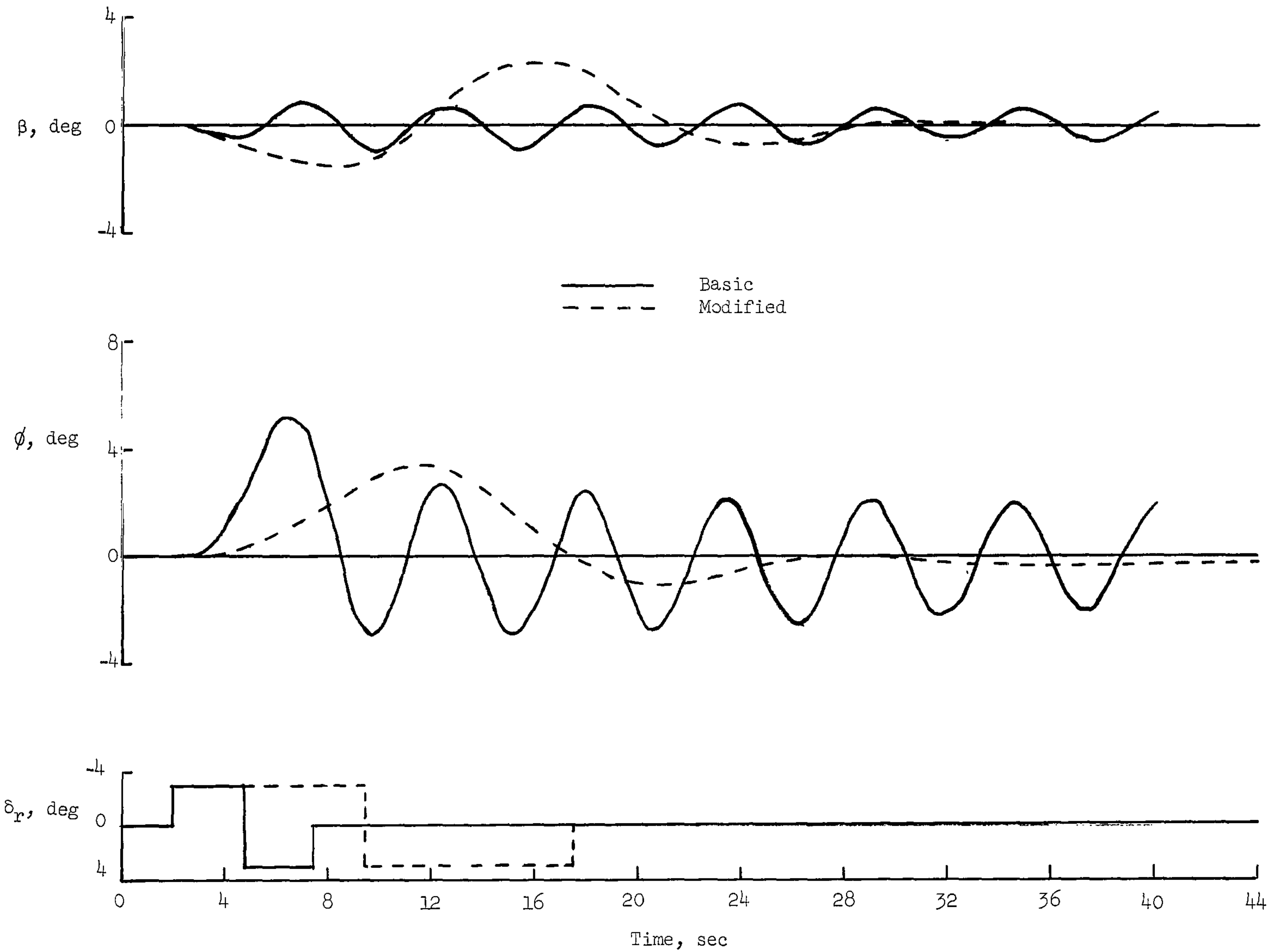


Figure 6.- Dutch roll characteristics of basic and modified canard-on configurations.

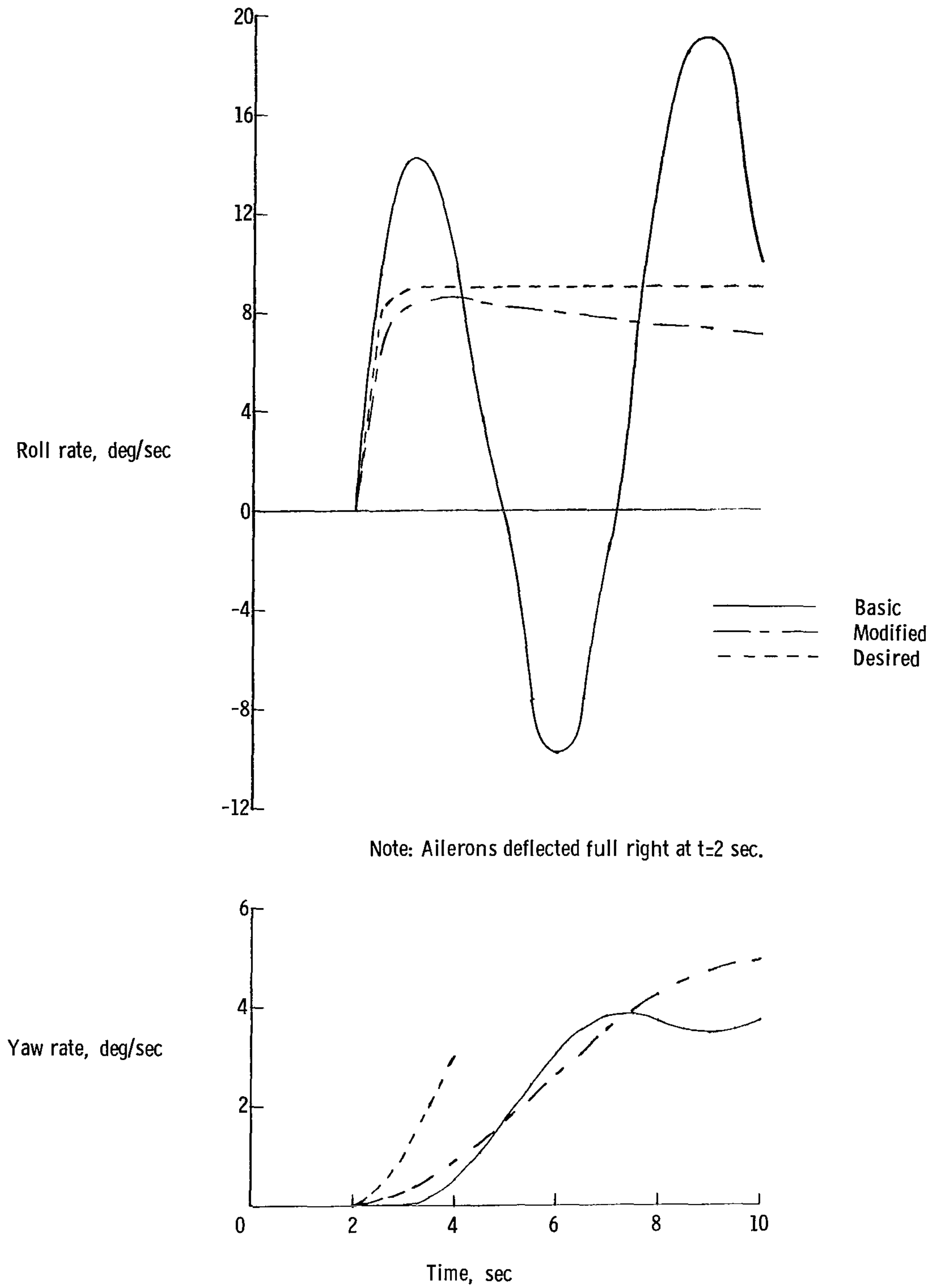
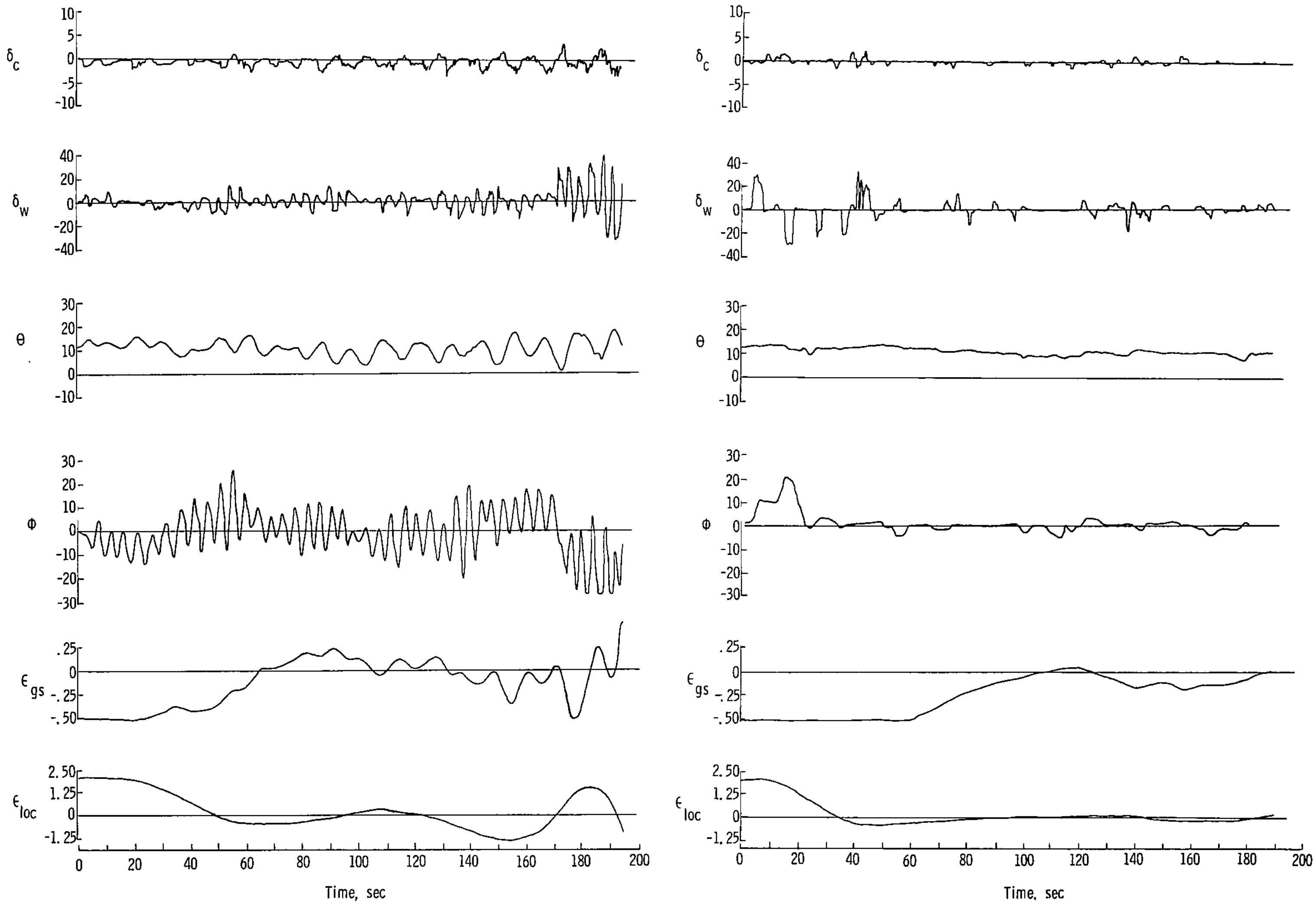


Figure 7.- Roll and yaw rate response to a full wheel step input.



(a) Basic configuration.

(b) Modified configuration.

Figure 8.- Typical approaches of the basic and modified canard-on configurations.

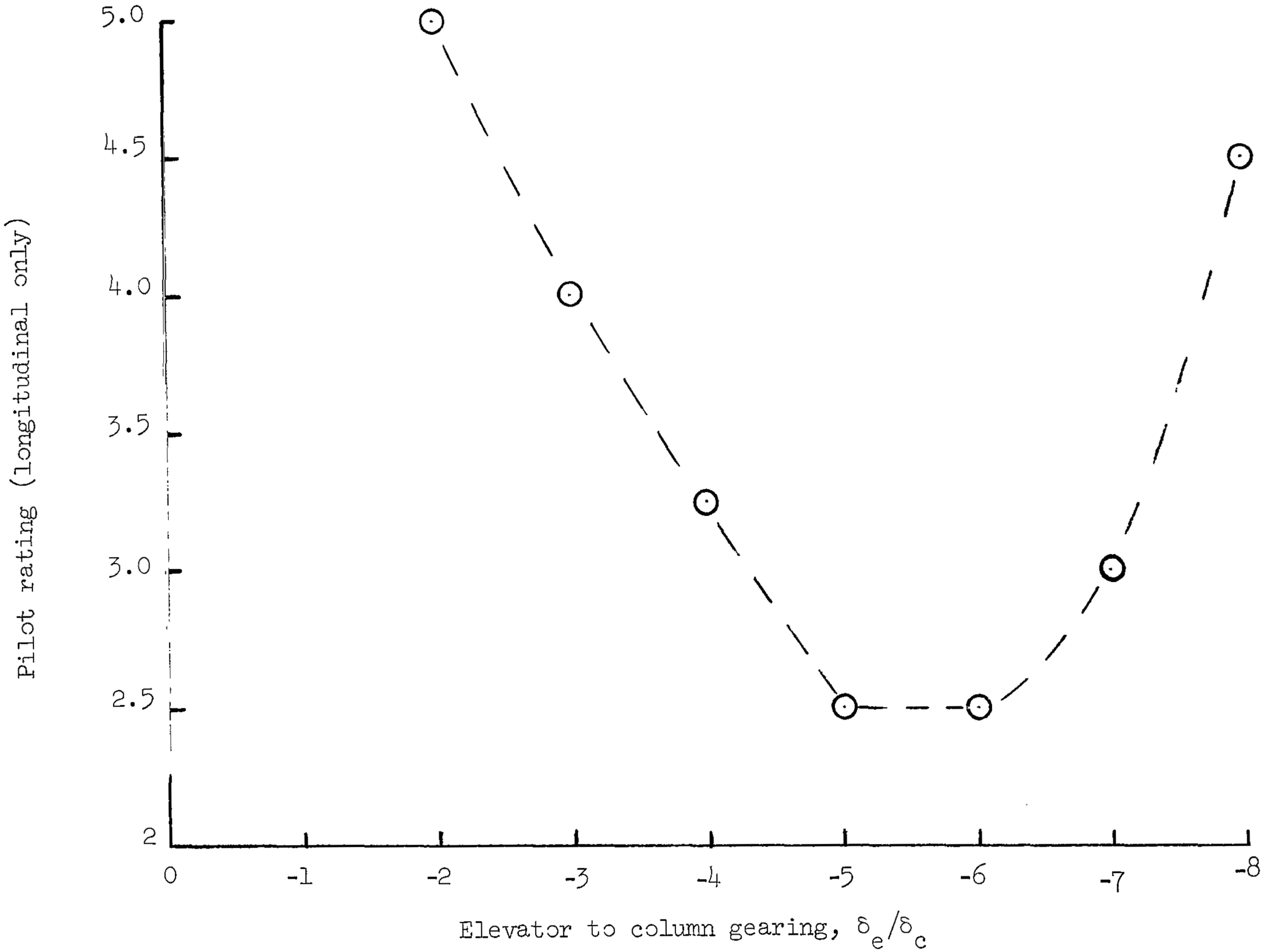
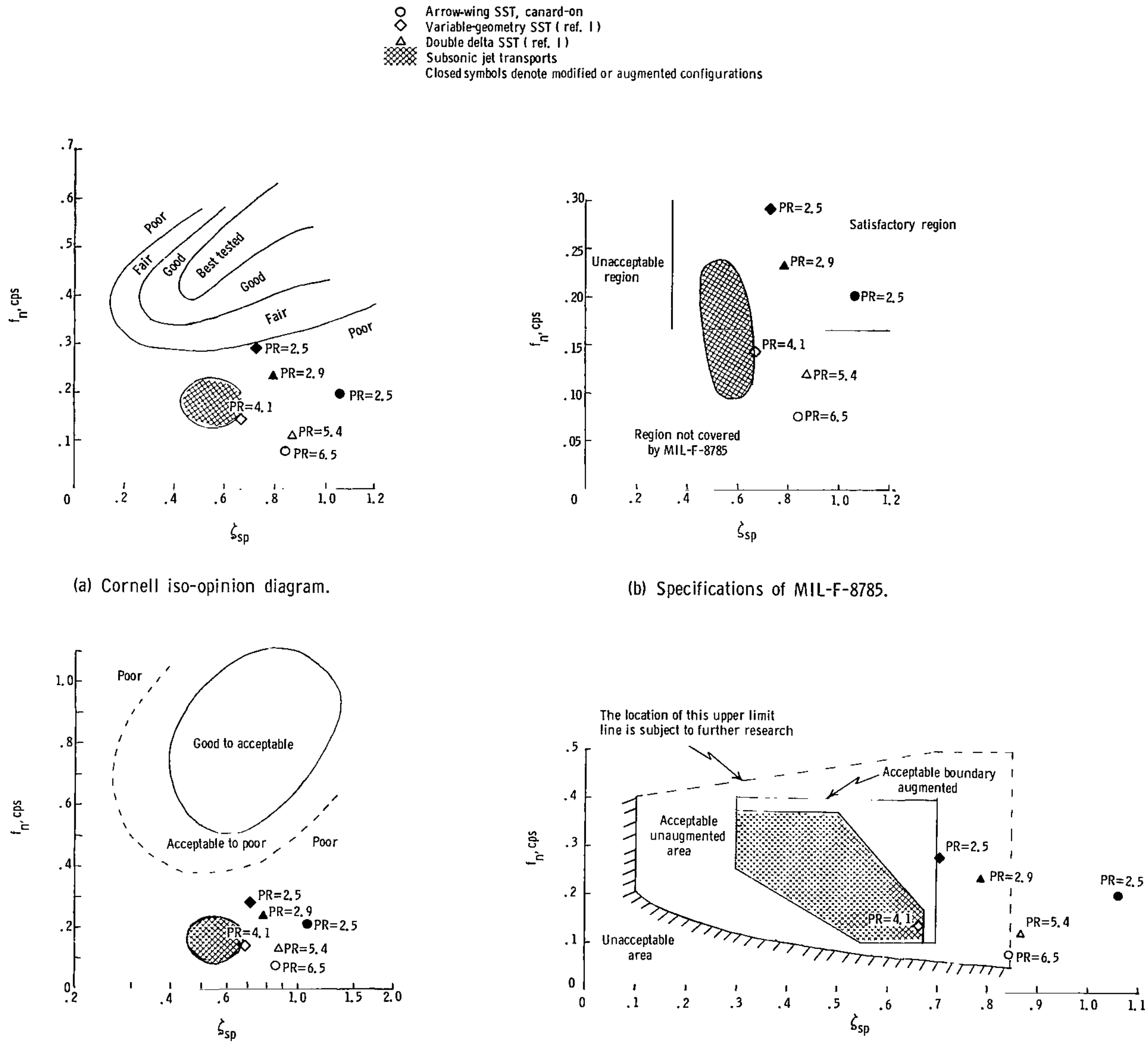


Figure 9.- Effect of elevator to column gearing on pilot rating for modified canard-on SST configuration.



(a) Cornell iso-opinion diagram.

(b) Specifications of MIL-F-8785.

(c) Criteria of reference 5.

(d) Criteria of reference 6.

Figure 10.- Comparison of the longitudinal handling qualities of SST configurations simulated in present study with those presented in reference 1, with those of current subsonic jet transports, and with existing handling qualities criteria.

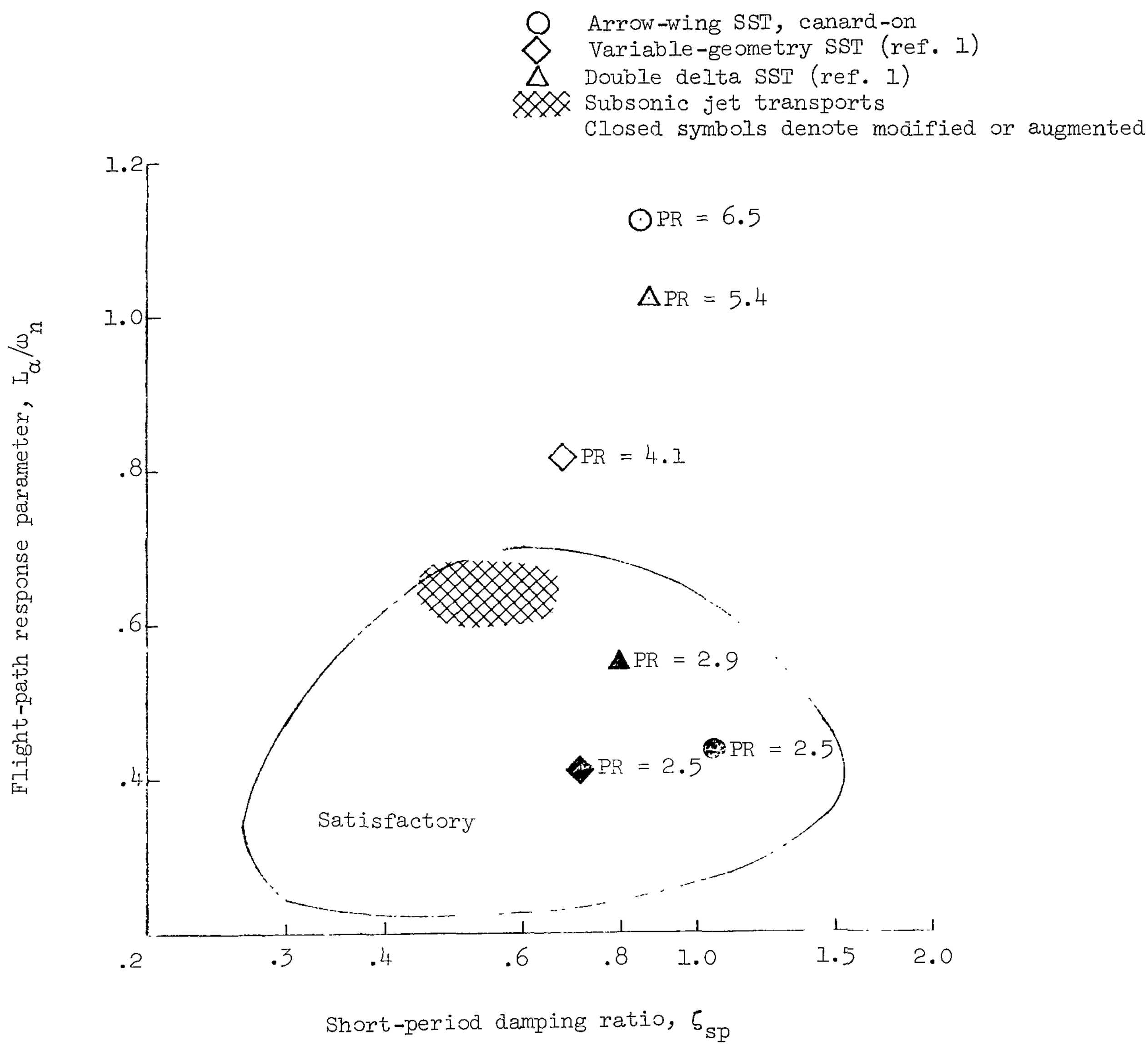


Figure 11.- Comparison of longitudinal short-period criterion of reference 7 with data for supersonic and subsonic jet transports.

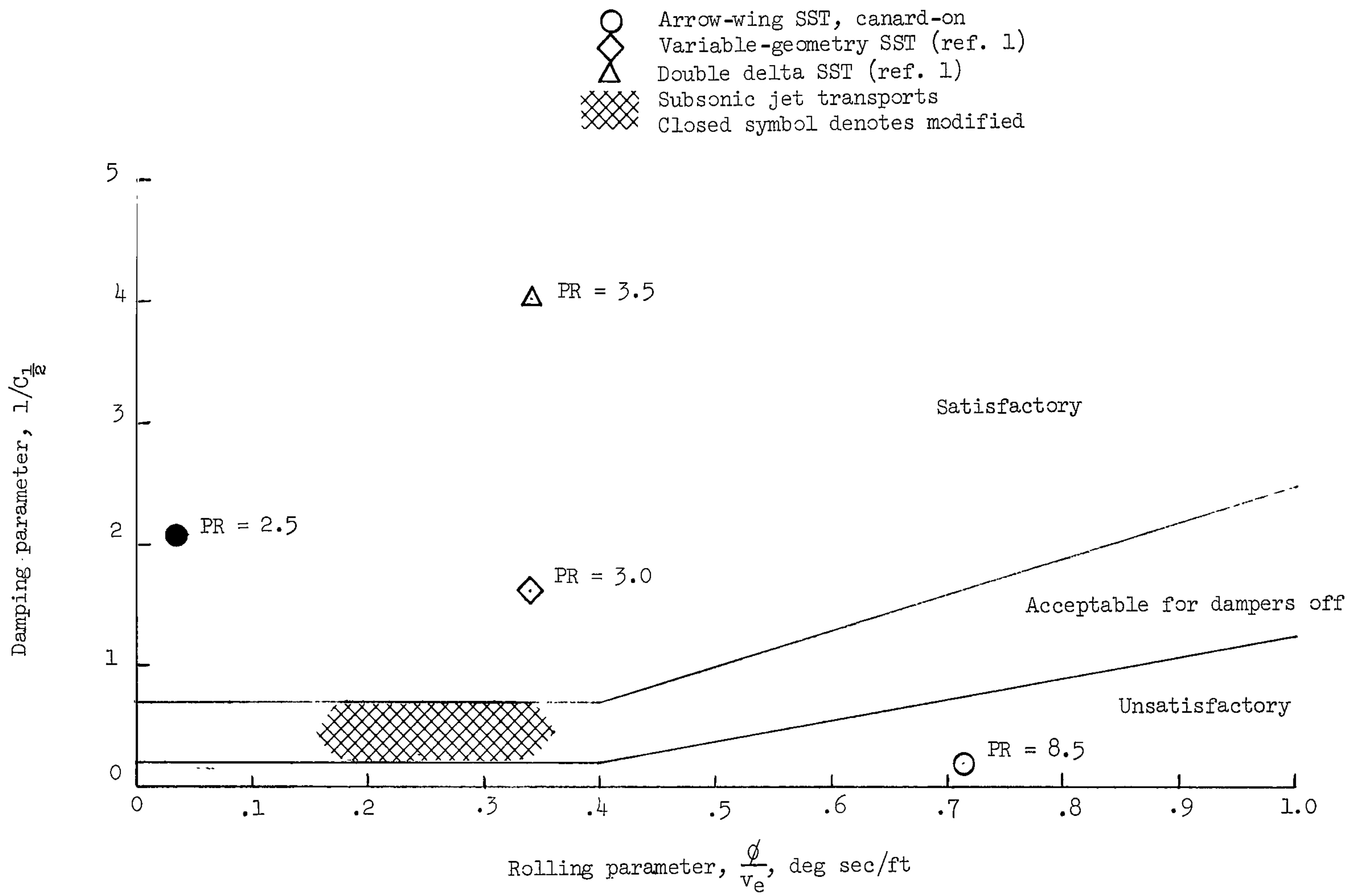


Figure 12.- Comparison of Dutch roll characteristics of the arrow-wing SST with those of SST configurations of reference 1 and with those of some large subsonic jet transports, all being related to existing military specifications.

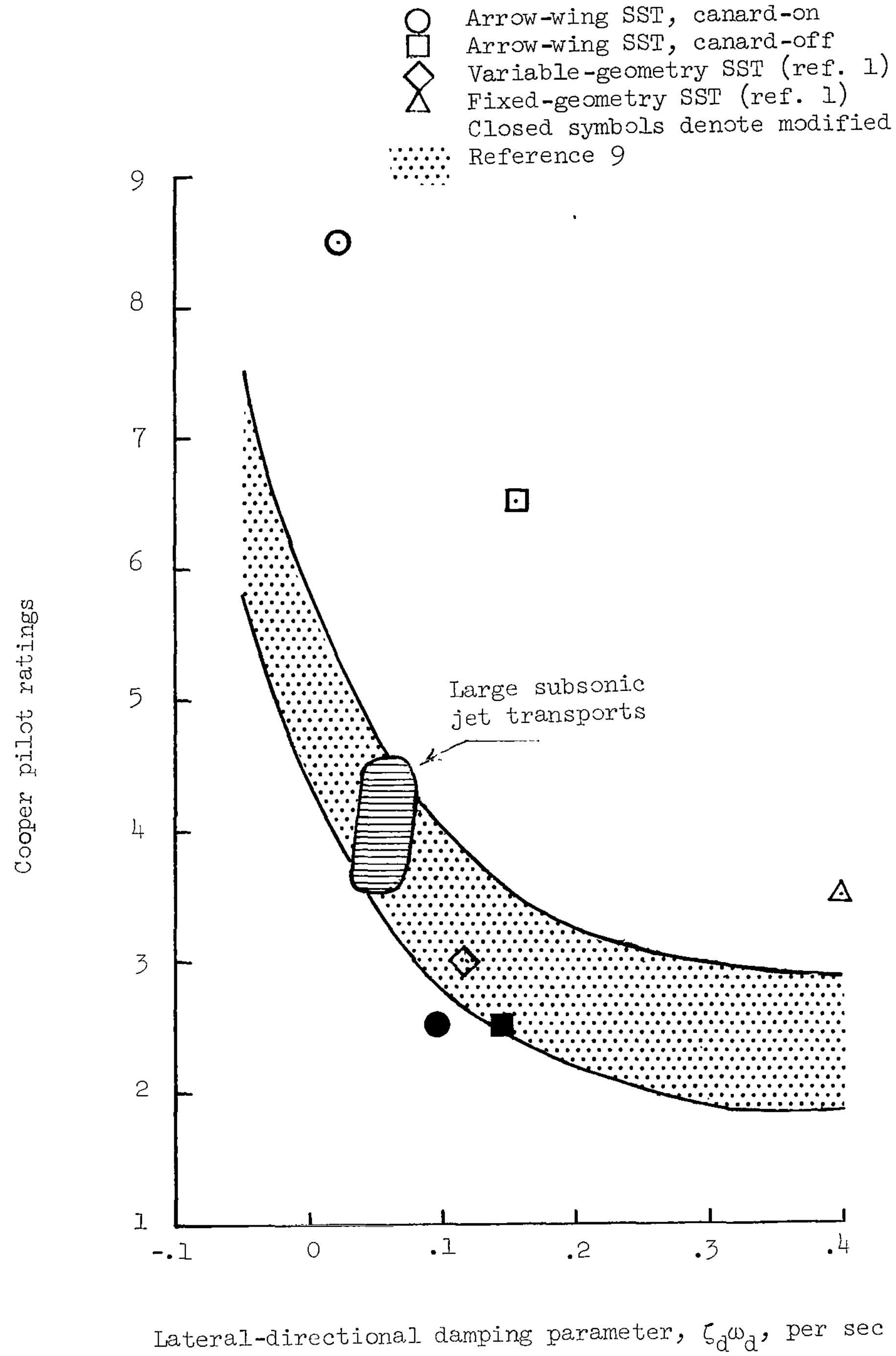


Figure 13.- Variation of pilot rating with lateral-directional damping parameters, $\zeta_d\omega_d$.

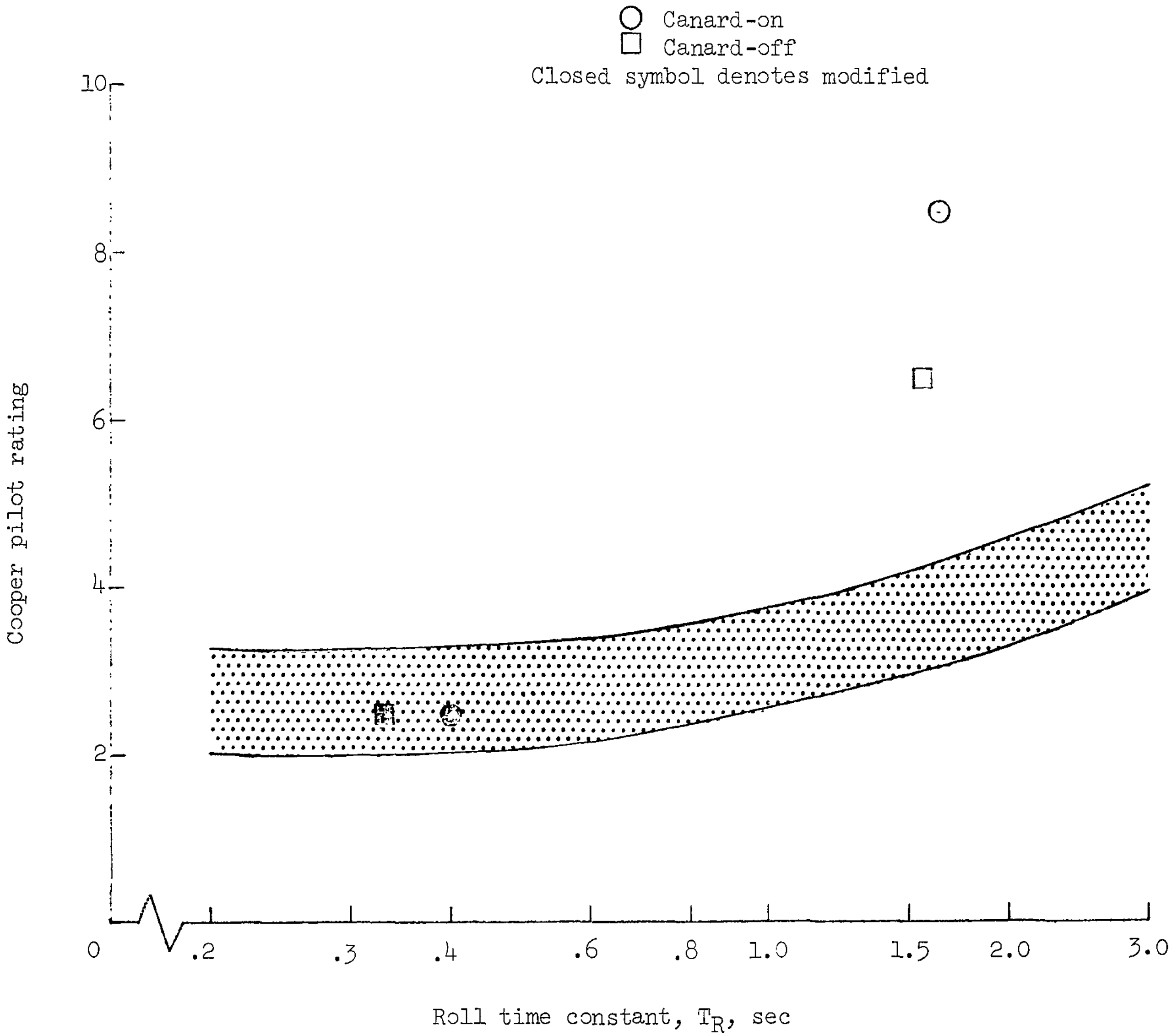
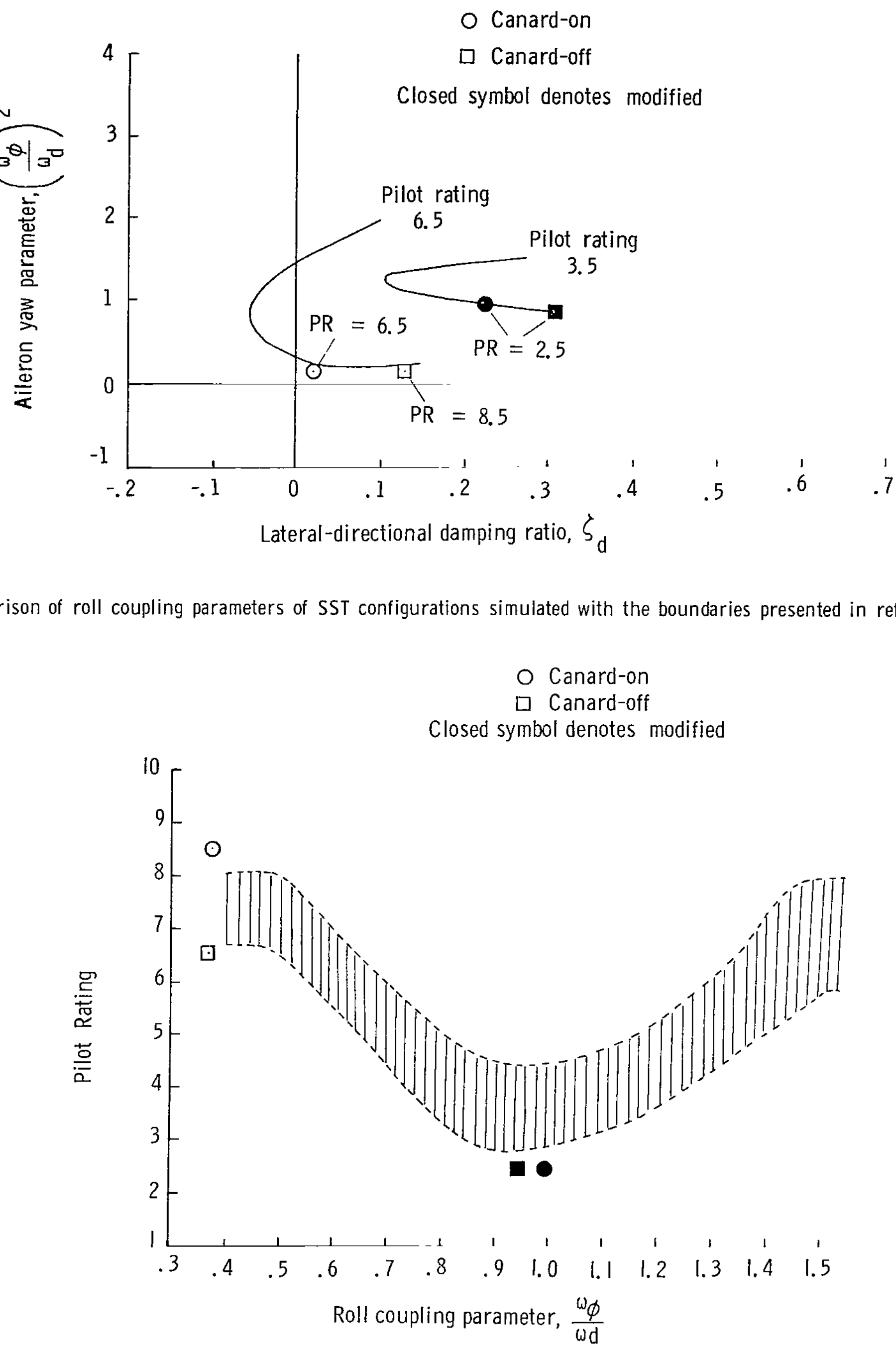


Figure 14.- Variation of pilot rating with roll time constant. (Shaded band represents fairings of results presented in ref. 10.)



(a) Comparison of roll coupling parameters of SST configurations simulated with the boundaries presented in reference 11.

(b) Variation of pilot rating with roll coupling parameter. (Shaded area was presented in ref. 12.)

Figure 15.- Comparison of roll coupling parameter of SST configurations simulated with the results presented in references 11 and 12.

NASA-Langley, 1967 — 5 L-5557

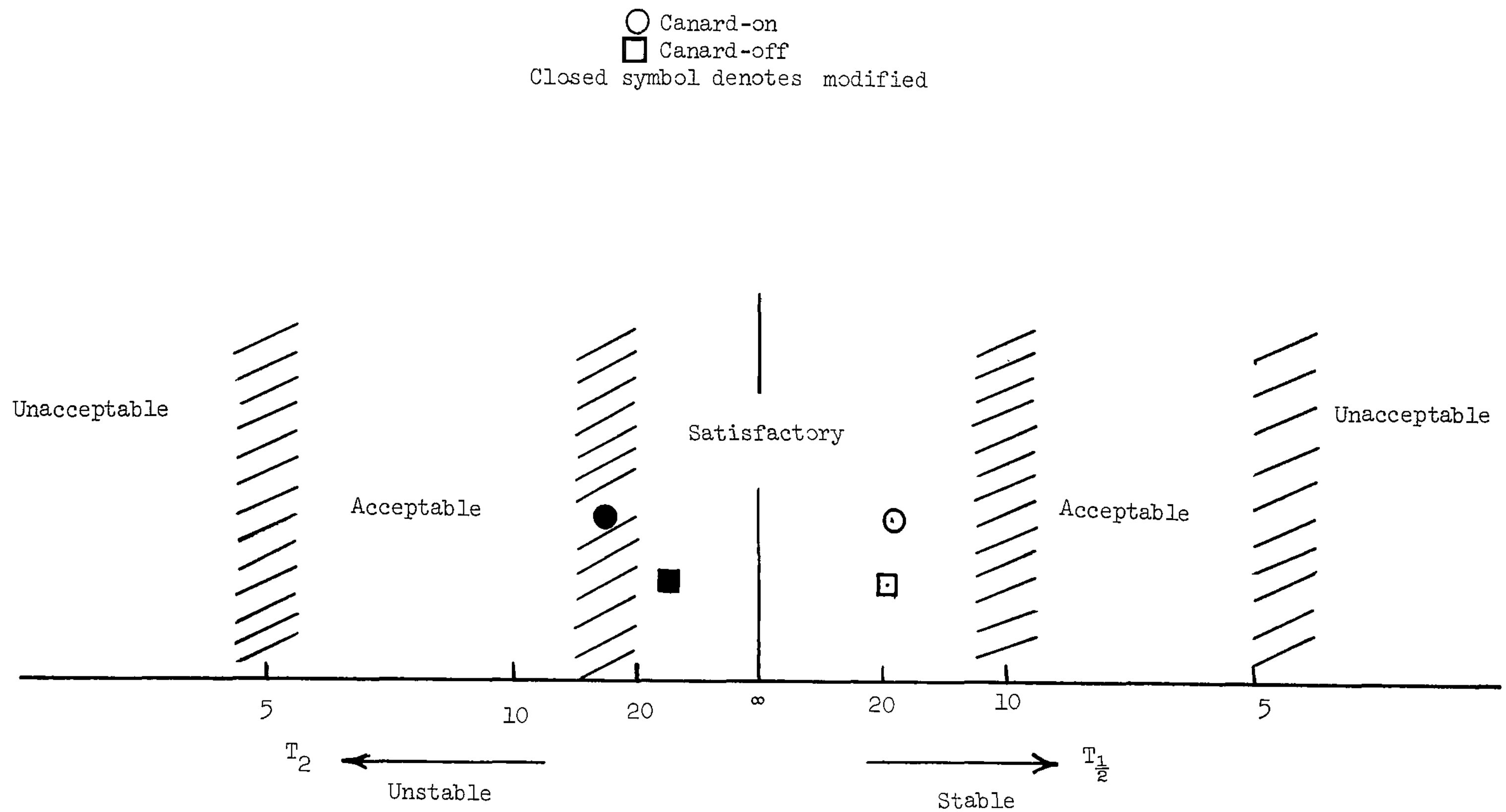


Figure 16.- Comparison of the spiral stability characteristics of the SST configurations with the criteria presented in reference 13.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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